Failure analysis of glass, carbon or Kevlar® fibre reinforced epoxy based composites in static loading conditions

Failure analysis of fibre reinforced plastics has developed into an useful tool that can provide helpful qualitative and quantitative information on the conditions and circumstances that led to composite failure This provides ample scope for effecting improvement in design and development of newer materials, in fracture control and avoid recurrence of failure in a similar environment

The thermosetting resins in general and particularly epoxy resins are by far the most widely used matrix systems for advanced structural composites and they account for more than two thirds of the present aerospace market mainly because of the formulations possible with them Carbon, glass and Kevlar composites are now being widely used in various geometries of reinforcement and formulations of resin Thus, failure analysis of these systems through tests approximating to actual service conditions, is indispensible

Failure analysis of advanced fibre/epoxy systems in the micromechanical and macroscopic level has been carried out by many researchers However, a single investigative report that encompasses the macro and micromechanical aspects of fracture, progressive fracture, failure and fibre- matrix interfacial failure sequences for epoxies, carbon/epoxy, glass/epoxy and Kevlar/epoxy systems, under identical conditions of fabrication and testing is unavailable

The present effort is hence an attempt to study the fracture and failure characteristics of the abovesaid composite systems in static loading conditions. More precisely the failure behaviour has been looked into from the point of view of

* Time-Temperature superposition in axial and non-axial compression tests in epoxies of two different formulations and their composites, with emphasis on deformation characteristics, macro and micromechanical aspects of failure, fibre-matrix interfacial failure sequences, comparison between failures in constant crosshead velocity and constant true strain rate, failure mode transitions and thermodynamic transitions

* Pin-ended buckling and bending behaviour of the Carbon/epoxy, Glass/epoxy and Kevlar/epoxy systems, characterisation of their mechanical behaviour for various geometries of reinforcement and specimen size, comparisons between buckling and bending in macroscopic and microscopic failure analysis through scanning electron

microscopy and Non-destructive C-Scan evaluation techniques

* Fracture mechanisms, fibre-matrix interfacial failure sequences for different epoxy based composites reinforced with woven fabric Translaminar and interlaminar tests with emphasis on interfacial conditions, curing, influence of voids and loading rates

* Elastic-plastic analysis of woven fabric Kevlar/epoxy composites in flexure and compression, contribution of shear and interlaminar shear strength of woven fabric Kevlar/epoxy composites, failure mode vs strain rate correlations and fracture feature analysis

To fulfil the aforementioned wide angled perspective of the problem, a broad spectrum in the testing modes viz . from axial compression to non axial and then pin ended compression, buckling /bending and three point flexural and shear loading, has been chosen Further, as the material behaviour varies from test to test, that combination of system and test method which yielded more interesting test results, has been discussed in detail compared to other systems, whereever found necessary

Certain aspects of the abovesaid investigations form the first reporting of their kind in the field of fibre reinforced plastics

Either an autoclave vacuum bagging or a compression moulding route was employed for the fabrication of laminates. For cylindrical specimens (unidirectionally reinforced or unreinforced) suitable split moulds were used Specimens with standard or non-standard geometries obtained by machining the laminates, were tested in a servohydraulic Instron or Dartec setup, as per requirements The surfaces of the failed regions of specimens were sputter coated with gold and viewed under a Scanning Electron Microscope (SEM) for a detailed fractographic analysis. In selected tests the ultrasonic C- Scan method was also employed for fracture analysis

Epoxies unidirectionally reinforced with either E glass fibres or T300 carbon fibres were axially or non-axially tested in compression at different crosshead velocities and true strain rates within the static domain at temperatures ranging from 25°C to 200°C, and their mechanical properties characterised. Unreinforced epoxies were tested for the same parameters so that the data could act as reference. The existing theories and models of Argon, Bowden, Brown and others for the deformation characteristics of glassy amorphous polymers were compared with the molecular and mechanical deformation of epoxies and their composites employed in this investigation, with special reference to the glass tran-

sition temperature 'Tg' and speed of testing Due comparisons were made between the employment of constant crosshead velocity and constant strain rate The studies reveal the similarities and distinctions in the deformation characteristics of epoxies and glassy amorphous polymers upto Tg The relationship between the shear stress and moduli at various temperatures and strain rates and evaluation of molecular parameters for epoxies, were looked into upto Tg Failure analysis involved construction of failure envelopes, studies on shear- buckling transition at a critical temperature, fibre-matrix interfacial failure sequences (explained with the shear-couple concept) and the influence of (ϵ, T) on the interfacial failures Studies on the possibilities of the occurrence of Adiabatic- isothermal transitions observed in some glassy amorphous polymers, proved otherwise in epoxies employed in the present work

* For pin-ended tests carried out with fibre reinforced epoxies, T300 carbon fibre/epoxy composite specimens with unidirectional and unidirectional crossply orientation and G802 woven fabric/epoxy specimens with various geometries, were employed. A special rig was designed and developed employing a varying combination of bending and compression Failure initiation and failure sequences at the midspan were monitored and established through high speed photography and substantiated with Non- destructive C-Scan evaluation techniques. In some specimen geometries, high compressive strains of the order of $\sim$ 1 85% for Pin-ended tests accompained by a higher load bearing capacity than conventional three point bend tests, were observed Further, the load deflection characteristics and hence the stress-strain characteristics were more non-linear in the pin-ended bend tests Fractographic investigations revealed features like delaminations in shorter specimens, well pronounced tensile and compressive zones depending on spans in buckling tests, and inplane microbuckling of fibres By virtue of loading it was seen that the pin-ended tests exerted a higher ratio of compressive to bending stress than three point tests Glass/epoxy and Kevlar/epoxy specimens were also tested and compared in a similar manner to make the study comprehensive

* As the interlaminar fracture mechanisms of woven fabric composites have been dealt in detail by many earlier investigators the translaminar fracture mechanism aspects of woven fabric composites and especially those reinforced with carbon and glass were examined in detail in the present work A detailed fractographic analysis of the fibre-matrix interfacial fibre sequences in the translaminar flexure of epoxy based

composites with different resin formulations, was carried out The influence of curing conditions, loading rates and voids on the modulus and strength revealed greater non-linearity in the composites containing higher void content due to increased misalignment of fibres Fracture mechanisms based on the fibre-matrix shear couple concept were propounded

* Finally, the elastic-plastic behaviour of woven fabric Kevlar/epoxy composites was analysed and modelled The observation of flexural strength being equal to or higher than the tensile strength in this composite, inspite of the low compressive strength due to kinking and yielding of the fibres was also explained based on the Weibull statistics A study involving various loading rates in the static domain revealed that 'looping' tendencies were observed in Kevlar fibres when tested in flexure at higher loading rates This feature was different from the helical ribbons of fibrils produced in tension Further,there was a clear evidence for a correlation to exist between strain rate and failure mode which had not been reported earlier Such looping tendencies were shown to be caused due to higher co-operative rotational isomeric deformation in fibres snapping back due to momentary recoil stresses that are compressive The interlaminar shear behaviour of woven fabric Kelvar/epoxy composites in three point loading was also studied for various span to depth ratios and explained A detailed analysis of the failure modes was carried out for various span to depth ratios and observed transition from tensile to shear mode of failure, explained based on the theoretical predictions. The explanation is based on the elastic-plastic model The apparent interlaminar shear strength obtained from short beam tests is shown to increase more than the predicted values, for a decrease in the span to depth ratio The true interlaminar shear strengths of the different woven fabric Kevlar/epoxy composites, were obtained from their apparent values The role of higher laminate thickness in enhancing the ILSS values was also discussed based on the beam elasticity. A detailed failure analysis involving visual methods and SEM examination of failure modes, transitions and shear fracture features were carried out and reported

The introduction to the subject matter of the thesis and the materials and methods employed are dealt in chapters 1 and 2 respectively. The findings are discussed in chapters 3 to 6 and the salient points derived from the investigations are summarised and concluded in chapter 7